A Detailed Study of the Effect of Breaking Waves on Microwave Polarimetric Emissivities

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LONG-TERM GOALS

Our long-term goals are to provide polarimetric microwave emissivities data that can be used to test models for predicting the microwave electromagnetic response of a foam-covered water surface and to develop better wind vector retrieval algorithms for satellite-mounted microwave radiometers.

OBJECTIVES

We will provide a detailed look at the physical processes affecting the microwave radiometric signal from breaking waves and foam patches by measuring the microwave polarimetric emissivity and microphysical structure of reproducible breaking waves in a saltwater surf pool.

APPROACH

Recent data have indicated that wind speed and direction can be measured using passive microwave radiometers [*Piepmeier and Gasiewski*, 2001; *Wentz*, 1992; *Wick et al.*, 2000; *Yueh et al.*, 1999; *Yueh et al.*, 1997; *Yueh et al.*, 1995] and the WindSat passive polarimetric satellite instrument is currently operating to provide the initial proof-of-concept satellite data. Multi-frequency radiometers are an attractive method for satellite-based wind measurements because they also provide estimates of sea surface temperature, sea-ice coverage, rain rate, water vapor concentration, and cloud water content. For this reason, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) has chosen to use passive polarimetric radiometry to fulfill the ocean surface wind vector environmental data record. This puts particular emphasis on ensuring wind vector retrieval algorithms used by the Conical Microwave Imager/Sounder (CMIS) currently under design by NPOESS accurately model the physical processes affecting the sea surface microwave brightness temperatures.

Because the radiometric signals needed for retrieving the wind direction are only a few degrees Kelvin at most, accurate retrieval of vector wind fields from microwave radiometric data requires understanding how microwave emissivity is determined by ocean surface properties. It is also critical to understand how this emissivity varies as a function of azimuthal look angle of the radiometer with respect to the wind vector. Although it is known that the ocean surface emissivity is primarily a function of the surface roughness and the fractional area coverage of breaking waves and foam, the dependence of the emissivity of foam on both incidence angle and azimuthal angle have not been characterized.

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In collaboration with Dr. L. A. Rose from the Naval Research Laboratory in Washington D.C. and Prof. S. Reising from the University of Massachusetts, we have conducted a series of field experiments that have provided a more thorough understanding of the relationship between foam, breaking waves, surface roughness, and microwave emissivity. The first of these experiments was conducted in May 2000 on the Chesapeake Bay using a specially designed foam generator. This device generated a uniform, stable patch of foam on the water surface. A crane was used to position an X-band (10.8 GHz) and a Ka-band (36.5 GHz) radiometer over the foam raft so that the emissivity of beam-filling foam could be measured as a function of radiometer incidence angle. The data show that for all polarizations and incidence angles measured, the foam emissivity is significantly less than one, which implies that ocean surface foam should not be modeled as a blackbody with an emissivity of one [*Rose et al.*, 2002].

In order to collect data to investigate the polarimetric emissivities of breaking waves, in September 2000, radiometric, foam coverage, and air-sea interaction data were collected from the R/P FLIP during the Fluxes, Air-Sea Interaction and Remote Sensing (FAIRS) experiment for wind speeds of up to 15 m/s with concomitant large-scale breaking waves. The data from this experiment suggested that the emissivity of a whitecap is not constant over its temporal evolution. Furthermore, the data also suggest that the decaying foam patch left in the wake has a higher emissivity than the actively breaking crest and that there are subtle differences in the emissivity of the breaking wave as a function of azimuthal angle. However, the intermittent and spatially sparse nature of oceanic breaking waves makes it difficult to acquire repeated measurements of beam-filling foam.

As the next step in assessing the effect of breaking waves on ocean remote sensing using passive microwave instruments, the main goal of this project has been to measure the polarimetric microwave emissivities of breaking waves as a function of the incidence angle, azimuthal look angle and time evolution of the breaking wave. Rather than attempt these measurements in the open ocean for wind-driven breaking waves, which would require a sizeable investment in time and money, it was decided to study the breaking of mechanically generated waves in a surf pool. Because surf pools generate reproducible breaking waves at a known location, they have been found to be an extremely cost-effective method of acquiring detailed information on the relationship between breaking waves, air-water gas exchange, and microwave brightness temperature [*Asher et al.*, 1995; *Asher et al.*, 1998].

WORK COMPLETED

Our major effort completed this year was the execution of the Polarimetric Emissivity of Whitecaps Experiment (POEWEX) conducted in October 2002 at the OHMSETT wave basin in Leonardo, New Jersey. OHMSETT was used because it was the only site identified that was outdoors with large enough dimensions (i.e., 200-m long by 20-m wide) and filled with seawater. A removable shoal was built and installed in OHMSETT to generate reproducible breaking waves at a fixed location in the wave basin. Three fully polarimetric microwave radiometers were used, a 10.8 GHz unit from the Naval Research Laboratory, and two radiometers from the University of Massachusetts, one at 19 GHz and one at 36.5 GHz. Figure 1 shows an overview of the breaking waves and the crane used to mount the microwave radiometers. The POEWEX wave-characterization instruments deployed were two acoustic-Doppler anemometers, an array of three precision pressure transducers for recording wave height profiles in the breaking zone, two void fraction meters for measuring air entrained by the breaking waves, an underwater camera for measuring the bubble size spectra, and a 14 GHz Doppler radar for estimating surface roughness. Analysis of the POEWEX data set is nearing completion and it is expected that several papers will result from the experiment.

Figure 1: Overview photograph of the OHMSETT wave basin showing the radiometers, mounting crane, and breaking waves generated on the shoal.

RESULTS

Figure 2 shows a series of three video images of breaking waves at the OHMSETT facility recorded during POEWEX at three different azimuthal angles. These images show that the fractional area foam coverage seen by the radiometer is a function of azimuthal angle because the wave can hide parts of the breaking crest depending on the azimuthal angle. This is clearly seen by comparing the video image for the azimuthal angles of 0˚ and 180˚. In the case of 0˚, the entire breaking crest is visible in the video image. However, at 180˚, the back side of the wave obscures the view of the breaking crest. Although these images are of different breaking waves, the waves in the wave basin were very similar in their overall characteristics so the differences between the two images is not due to a change in the waves between the two images. This dependence of foam coverage on azimuthal look angle also affects the brightness temperatures measured by the radiometers.

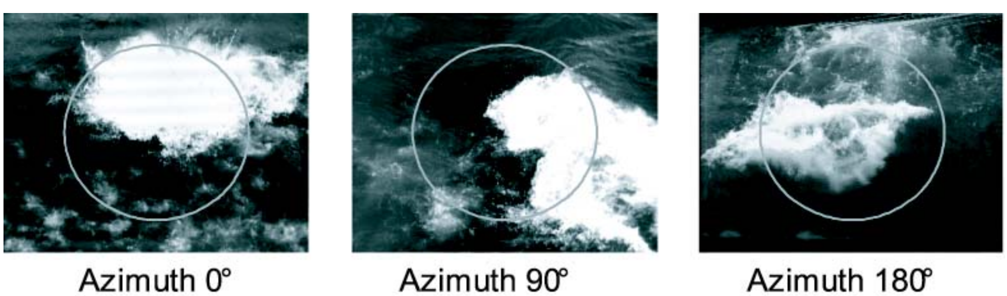

Figure 2: Video images of breaking waves in the OHMSETT wave basin at three different azimuthal look angles showing the steric effects of the wave in measuring the fractional area foam coverage generated during wave breaking. The gray circle shows the footprint of the radiometers in the image.

Figure 3 shows the increase in the apparent microwave brightness temperature of the water surface for horizontal polarization at 19 GHz and 36.5 GHz as a breaking wave passes by the microwave radiometers. The increase in brightness temperature is due to the foam and bubbles generated by the breaking wave raising the water surface emissivity. This explains why the increase is highly correlated with the fractional area foam coverage as measured from the video images in Figure 2. The shadowing effect of the wave is seen in the data where the largest increases in brightness temperature are found for azimuthal angles where the back side of the wave does not block the radiometer's view of the foam.

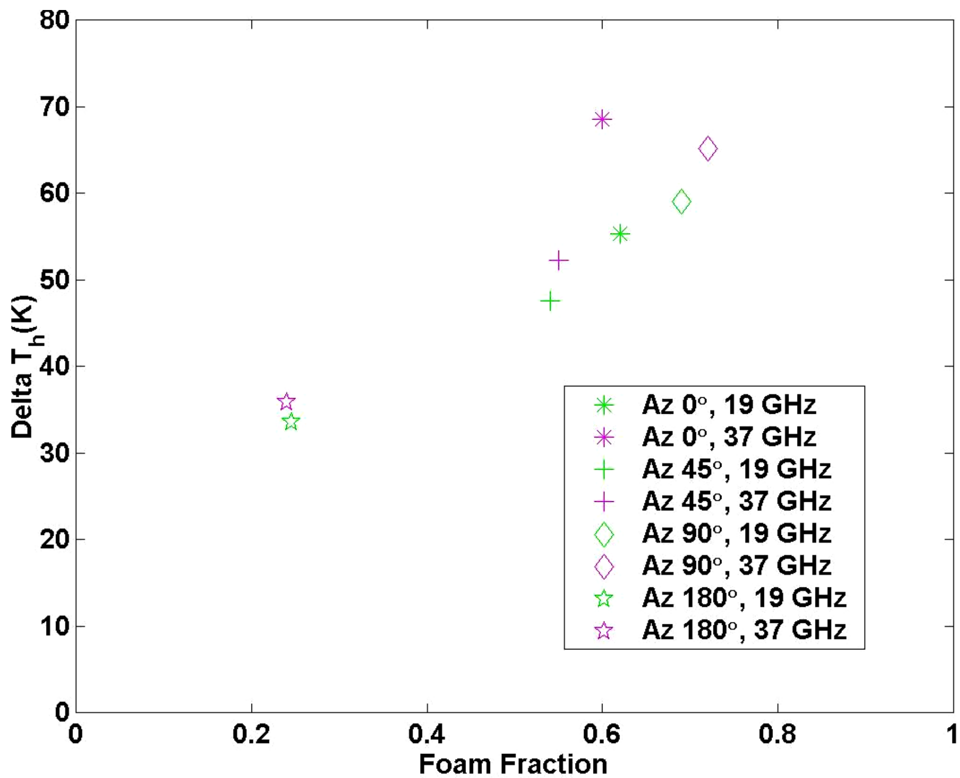

Figure 3: Plot of the increase in the horizontally polarized apparent microwave brightness temperature due to the passage of a breaking wave as a function of azimuthal look angle. All data for an incidence angle of 53º.

Figure 4 shows a time series of wave height and void fraction measured in the breaking wave at a depth of 30 cm based on the calm water surface. The maximal in the void fraction record are caused by bubble clouds injected into the water column by the breaking wave. It appears that the maximal in void fraction are correlated with wave troughs. The void fraction data, wave height data, and surface video data will be used to investigate the relationship between the visible features of the breaking wave and the radiometric signal.

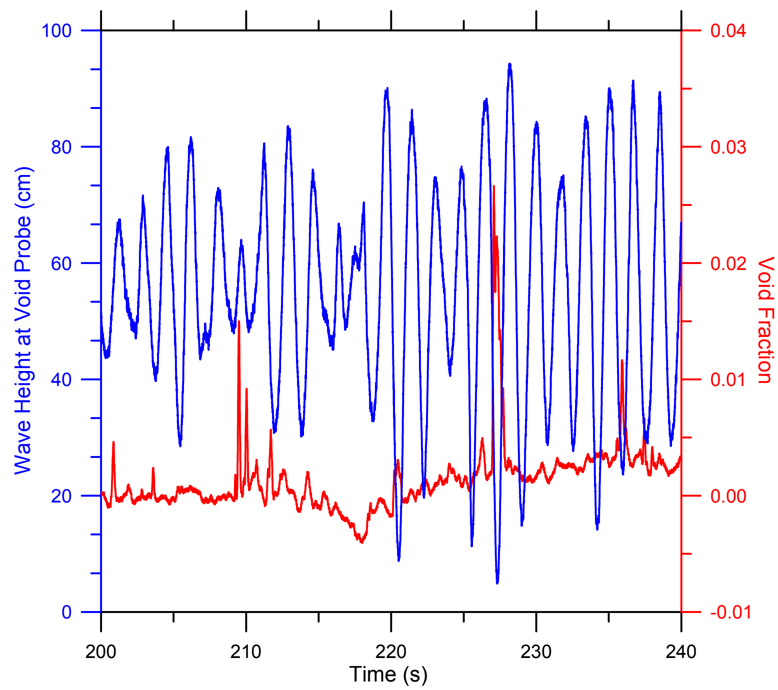

Figure 4: Time series of wave height and void fraction measured within the radiometer footprint during POEWEX.

IMPACT/IMPLICATION

POEWEX provides the first detailed study of the polarimetric microwave emissivities of breaking waves. As such, the data will be valuable for developing parameterizations of the emissivities of oceanic breaking waves, and in designing future experiments for calibrating and validating the performance of the WindSat microwave polar meter. Data from POEWEX will also be useful in designing and evaluating the errors in retrieval algorithms for CMIS.

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Chen, D., L. Tsang, L. Zhou, S. C. Reising, W. Asher, L. A. Rose, K. H. Ding, and C.-T. Chen, 2003. ``Microwave Emission and Scattering of Foam based on Monte Carlo Simulations of Dense Media," *IEEE Trans. Geosci. Rem. Sens.*, **41**, 782-790.

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CONFERENCE PRESENTATIONS

Reising, S.C., S. Padmanabhan, M.A. Aziz, W.E. Asher, L.A. Rose, and P.W. Gaiser, “Microwave Emission of Reproducible Breaking Waves: The POlarimetric Emissivity of Whitecaps Experiment (POEWEX '02),” *IEEE International Geoscience and Remote Sensing Symposium*, Toulouse, France, July 2003.

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AWARDS/HONORS

Sharmila Padmanabhan, graduate student in the Department of Electrical and Computer Engineering, University of Massachusetts at Amherst. Second Prize for the 2003 Student Paper Prize Award. IEEE International Geoscience and Remote Sensing Symposium (IGARSS '03) in Toulouse, France.

Steven C. Reising, assistant professor in Department of Electrical and Computer Engineering, University of Massachusetts at Amherst. The 2003 Certificate of Recognition for recognition and appreciation of valued services and contributions as the IEEE Geoscience and Remote Sensing Society Newsletter Editor, 2000-2003. Presented at the IEEE International Geoscience and Remote Sensing Symposium (IGARSS '03) in Toulouse, France.